

Flow Characterization of Peach Products During Extrusion

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ABSTRACT: Suitability of Bingham, Herschel-Bulkley, Casson, and Mizrahi-Berk models, to characterize the flow behavior of peach products during extrusion was investigated. The Casson equation sufficiently described the flow of peach extrudates within the 49 to 125 s⁻¹ shear rate range. As concentration increased, yield stress and consistency coefficients increased. A rheological model was proposed to describe the viscosity of peach extrudates. The model incorporates the effect of shear rate by the Casson equation and the effect of concentration by a linear expression. The model provided good fit to the experimental data for peach extrudates reconstituted from drum-dried peach purees.

Key Words: extrusion, viscosity, yield stress, Casson model, modified peach puree

Introduction

MANY FRUITS CAN BE UTILIZED IN THE FORM OF “RESTRUCTURED fruit products.” This not only provides a new outlet for the imperfect or surplus fruit but also an alternative to conventional fruit-based confectionery snacks. This type of food product aims to be 100% fruit and free of stabilizers, added sweeteners, gelling agents, thickeners, salt, and lipids. Restructured fruit products contain high levels of solids; hence, they are highly viscous. Processing and especially final shaping of such fruit products could be inefficient by using conventional techniques such as molding. Twin screw extruders possess efficient conveying capabilities, provide good control of residence time, mixing, and shear. They also offer flexibility of processing conditions and can handle highly viscous materials.

Many researchers have used power law model to describe the flow properties of fruit products (Charm 1960; Harper and El Sahrigi 1965; Saravacos and Moyer 1967; Saravacos 1968; Rao and others 1981; Barbosa-Canovas and Peleg 1983; Dickie and Kokini 1983; Dervisoglu and Kokini 1986; Hassan and Hobani 1998; Hobani 1998; Ibanoglu and Ibanoglu 1998) at soluble solids concentrations as high as 70 °Brix. Even though viscosity data shows good fit to a power law equation, the model does not account for a yield stress. Yield stress represents a finite stress required to achieve flow. For process design and quality assessment, yield stress is a very important characteristic because it is related to the mouthfeel (Steffe 1996).

Several models are potentially applicable to describe the behavior of concentrated peach products during extrusion. The Bingham model is the simplest equation that accounts for a yield stress. Butter, margarine, and honey are examples of Bingham model foods (Mackey 1989). The Herschel-Bulkley (HB) model is one of the most extensively used equations to describe the flow characteristics of shear-thinning fluids over a wide shear rate range (Steffe 1996). Rao and others (1981), Rao and Cooley (1983), Yoo and Rao (1995), and Missaire and others (1990) successfully used the HB model to describe the rheological behavior of tomato products with total solids up to 36%. HB adequately described the flow behavior of banana, peach, papaya, and mango purees with Brix 12 ° to 52 ° at various temperatures and pHs in studies reported by Guerrero and Alzamora (1998a,b). The Casson model has been used to describe the flow behavior of tomato concentrates (Rao and others 1981), apple sauce (Barbosa-Canovas and Peleg 1983; Dervisoglu and Kokini 1986; Qiu

and Rao 1988; Missaire and others 1990), and furcellaran gum (Rao 1977). It was initially developed by Casson (1959) for pigment suspensions (Mackey 1989). The Mizrahi and Berk (MB) equation, which is a modified Casson equation, was successfully used for flow characterization of concentrated orange juice at 60 to 65 °Brix (Mizrahi and Berk 1972).

Prediction and mathematical representation of flow characteristics of fruit products is necessary for optimum design of the unit operations for the process and better control of the final product quality. However, the conditions of high solids applied for restructured fruit foods from partially reconstituted drum-dried purees have not been examined. This study determines the flow characteristics in the formation of high solids extruded peach products from this raw material. The applicability of different models for describing the rheological behavior was also examined. The effect of peach puree concentration on the model parameters was analyzed.

Results and Discussion

FLOW CHARACTERISTICS OF EXTRUDED PEACH PUREE PRODUCT were studied at constant temperature (40 °C) and screw speed (200 rpm). The effect of concentration (total solids) on the flow parameters of peach extrudates was evaluated. The concentration of peach puree varied from 67 to 75% (w/w, dry basis). The total mass flow rate inside the barrel was varied from 28 to 64 g/min at each moisture. Below 28 g/min flow rate, the flow in the barrel was insufficient to develop a constant die pressure. The extruder was not able to handle flow rates higher than 64 g/min at the given conditions due to a high degree of barrel fill.

At each flow rate, melt pressure readings at 3 points along the slit die were collected. By using this pressure drop and the dimensions of the die, shear stress and shear rate were calculated, and shear rate was corrected by Rabinowitsch-Mooney equation (Steffe 1996):

$$\sigma_w = \Delta P h / 2L \quad (1)$$

$$\dot{\gamma}_w = \Gamma / 3 [2 + (d(\ln \Gamma) / d(\ln \sigma_w))] \quad (2)$$

and

$$\Gamma = 6\dot{Q} / wh^2 \quad (3)$$

where σ_w is the wall shear stress (Pa), Γ is the wall shear rate (1/

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s), $\dot{\gamma}_w$ is the corrected wall shear rate (1/s), ΔP is pressure drop along the slit die (Pa), \dot{Q} is the volumetric feed rate (m³/s), w is the width of the slit die (m), h is the height of the slit die (m), and L is the length between the pressure transducers which ΔP is measured.

The apparent viscosity of the melt is the ratio of wall shear stress to corrected wall shear rate (Steffe 1996):

$$\eta = \sigma_w / \dot{\gamma}_w \quad (4)$$

where η is in Pa · s. Apparent viscosity calculated by Eq. 4 is called experimental viscosity throughout this work.

A plot of rheological data suggested the presence of yield stress at all concentrations. Four models (Bingham, Herschel-Bulkley, Casson, and Mizrahi-Berk) were used to describe the flow property data of 100% extruded peach puree products.

The Bingham model assumes that once the yield stress has been exceeded, Newtonian behavior occurs:

$$\tau = \tau_{0B} + K_B \dot{\gamma} \quad (5)$$

where τ is shear stress (Pa), τ_{0B} is Bingham yield stress (Pa), K_B is Bingham consistency coefficient (Pa · s), and $\dot{\gamma}$ is shear rate (s⁻¹).

The Herschel-Bulkley (HB) model is a generalized power law equation with a yield stress added:

$$\tau = \tau_{0H} + K_H \dot{\gamma}^{n_H} \quad (6)$$

where τ_{0H} is HB yield stress (Pa), K_H is HB consistency coefficient (Pa · s ^{n_H}), and n is HB flow behavior index (dimensionless). For shear-thinning fluids n is less than 1.

Casson model has been designated as the official method for determining the yield stress of chocolate samples (Rao 1977). It is expressed by:

$$\tau^{0.5} = \tau_{0C}^{0.5} + (\mu_{\infty} \dot{\gamma})^{0.5} \quad (7)$$

where τ_{0C} is the Casson yield stress (Pa) and μ_{∞} is the high-shear limiting viscosity (Pa · s). The drawbacks seen with power law and HB equations (zero viscosity at infinite shear rates and infinite viscosity at zero shear rates) do not apply to the Casson model.

Mizrahi and Berk (MB) (1972) proposed a modification of Casson equation by including a variable flow index:

$$\tau^{0.5} = \tau_{0M}^{0.5} + K_M (\dot{\gamma})^{n_M} \quad (8)$$

where τ_{0M} is MB yield stress (Pa), K_M is MB consistency coefficient (Pa^{0.5} · s^{- n_M}), and n_M is MB flow index (dimensionless).

Tables 1, 2, 3, and 4 present complete results of application of these models. All 4 models include a yield stress. Magnitude of the estimated yield stresses varied greatly depending on the model used (Fig. 1). The yield stress predictions by the Bingham model was the highest, followed by the Casson model's. The MB model predicted the lowest yield stresses; however, MB and HB yield stresses were comparable in magnitude at all concentrations. Rao and Cooley (1983) found that HB and MB models predicted comparable magnitude of yield stresses in case of tomato concentrates with 30% total solids. Magnitudes of the yield stresses of the peach extrudates were also dependent on the concentration. For all 4 models, the higher the concentration, the higher the yield stress estimates (Fig. 1). Rao and others (1981) and Rao and Cooley (1983) observed an exponential increase in yield stress as total solids of tomato concentrate samples increased from 6 to 36%.

Regardless of the model used, yield stresses observed in this

Table 1—Flow parameters obtained using the Bingham model (Eq. 5) and asymptotic 95% confidence intervals (CI) of parameters

Concentration (%, w/w)	τ_{0B} (Pa)	τ_{0B} lower CI	τ_{0B} upper CI	K_B (Pa · s)	K_B lower CI	K_B upper CI	R ²
67	4293	4056	4530	27.3	24.3	30.4	0.988
69	5045	4921	5170	32.0	30.5	33.6	0.994
71	5299	5158	5419	43.4	41.8	45.3	0.995
73	5920	5489	6352	41.6	36.6	46.6	0.986
75	8243	7733	8753	54.1	47.6	60.7	0.986

Table 2—Flow parameters obtained using the Herschel-Bulkley model (Eq. 6)

Concentration (%, w/w)	τ_{0H} (Pa)	n_H	K_H (Pa · s ^{n_H})	R ²
67	1695	0.436	713.4	0.993
69	2051	0.448	785.6	0.997
71	2198	0.494	755.6	0.992
73	2340	0.487	819.2	0.990
75	3074	0.444	1363.9	0.999

Table 3—Flow parameters obtained using the Casson model (Eq. 7) and asymptotic 95% confidence intervals (CI) of parameters

Concentration (%, w/w)	τ_{0C} (Pa)	τ_{0C} lower CI	τ_{0C} upper CI	μ_{∞} (Pa · s)	μ_{∞} lower CI	μ_{∞} upper CI	R ²
67	2928.9	2671	3187	8.77	7.2	10.4	0.992
69	3383.4	3260	3506	10.62	9.8	11.4	0.996
71	3423.2	3254	3592	15.48	14.1	16.8	0.995
73	3760.9	3276	4246	15.24	11.9	18.6	0.988
75	5501.5	4956	6047	18.10	14.6	21.6	0.999

Table 4—Flow parameters obtained using the Mizrahi-Berk model (Eq. 8)

Concentration (%, w/w)	τ_{0M} (Pa)	n_M	K_M (Pa ^{0.5} · s ^{-n_M})	R ²
67	1580.2	0.319	10.11	0.993
69	2117.9	0.337	9.47	0.994
71	2325.4	0.389	8.28	0.990
73	2574.7	0.384	8.45	0.989
75	2882.0	0.322	14.32	0.993

study were considerably higher than the ones reported in the literature (Table 5). This difference reflects the much higher solids concentrations used here.

The magnitude of consistency coefficients obtained in this study was higher than the values reported in the literature (Tables 1 to 5). As concentration decreases consistency coefficient decreases with each of the models (Tables 1 to 4). Guerrero and Alzamora (1998a,b) and Grigelmo-Miguel and others (1999) reported similarly that as soluble solids content of samples in-

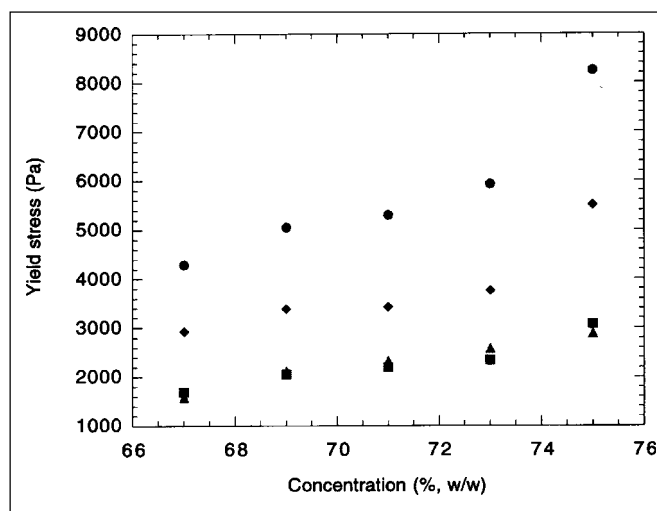


Fig. 1—Yield stresses estimated by Bingham, ●; Herschel-Bulkley, ■; Casson, ◆ and Mizrahi-Berk, ▲ equations as a function of concentration

Table 5—Rheological data for various fruit purees, sauces, concentrates, and juices

Material	Concentration ^a	T ^c	$\dot{\gamma}$ range ^d	Model	τ_0 ^{b,e}	n ^{b,f}	Reference
Peach puree ^g	67% to 75%	40	49 to 125	Casson	2929 to 5502	—	This study
Peach puree ^g	67% to 75%	40	49 to 125	Bingham	4293 to 8243	—	This study
Peach puree ^g	67% to 75%	40	49 to 125	HB	1695 to 3074	0.44 to 0.49	This study
Peach puree ^g	67% to 75%	40	49 to 125	MB	1724 to 2315	0.29 to 0.37	This study
Peach puree ^g	51 °	40	0.1 to 300	HB	2.7 to 2.9	0.67	Guerrero and Alzamora (1998b)
Mango puree	51 °	40	0.1 to 300	HB	3.6 to 8.0	0.59 to 0.69	Guerrero and Alzamora (1998b)
Mango pulp	16 °	25	0.1 to 1000	HB	3.5 to 3.9	0.38	Bhattacharya and rastogi (1998)
Banana puree	51 °	40	0.1 to 300	HB	5.3 to 6.7	0.58 to 0.64	Guerrero and Alzamora (1998a)
Apricot puree	12.5% to 15.3%	23	5 to 300	HB	22.1	0.59 to 0.79	Duran and Costell (1982)
Apple sauce	17 °	25	0.03 to 21	Casson	26.6 to 50.7	—	Qiu and Rao (1988)
Apple sauce	17 °	25	0.03 to 21	HB	18.4 to 46.4	N/R	Qiu and Rao (1988)
Apple sauce	17 °	25	0.03 to 21	MB	25.5 to 50.1	N/R	Qiu and Rao (1988)
Apple sauce	17 °	25	0.03 to 21	Bingham	62.6 to 82.2	—	Qiu and Rao (1988)
Apple sauce	N/R	23	0.005 to 1	Casson	57.8	—	Dervisoglu and Kokini (1986)
Apple sauce	N/R	23	0.005 to 1	Bingham	10.1	—	Dervisoglu and Kokini (1986)
Apple sauce	N/R	23	1 to 1600	HB	9.0	0.33	Dervisoglu and Kokini (1986)
Apple sauce	N/R	23	1 to 1600	Casson	28.1	—	Dervisoglu and Kokini (1986)
Apple sauce	18.1 °	25	0.1 to 300	HB	30	0.43	Barbosa-Canovas and Peleg (1983)
Apple sauce	18.1 °	25	0.1 to 300	Casson	37.2	—	Barbosa-Canovas and Peleg (1983)
Apple sauce	18.1 °	25	0.1 to 300	MB	29.2	0.35	Barbosa-Canovas and Peleg (1983)
Tomato paste	N/R	23	1 to 1600	HB	43	0.26	Dervisoglu and Kokini (1986)
Tomato paste	N/R	23	1 to 1600	Casson	167.7	—	Dervisoglu and Kokini (1986)
Tomato paste	5.6% to 36%	25	4 to 500	Casson	49 to 59.3	—	Rao and others (1981)
Tomato conc.	30%	40	20 to 1370	HB	109	0.53	Rao and Cooley (1983)
Tomato conc.	30%	40	20 to 1370	MB	102	0.45	Rao and Cooley (1983)
Conc. orange j.	65.3 °	30	N/R	HB	9.2	N/R	Vitali and Rao (1984)
Conc. orange j.	65.3 °	30	N/R	Casson	11.3	—	Vitali and Rao (1984)
Conc. orange j.	65.3 °	30	N/R	MB	2.6	N/R	Vitali and Rao (1984)
Conc. orange j.	65 °	25	8 to 512	HB	9.4 to 244	0.84 to 1.1	Crandall and others (1982)
Conc. orange j.	59 °	30	N/R	HB	1.5 to 24.4	0.84 to 1.1	Mizrahi and Berk (1972)

a Concentration, % total solids or °Brix

b The range reflects raw product variability and pH.

c Temperature, °C

d Shear rate, s⁻¹

e Yield stress, Pa

f Flow behavior index, dimensionless

g Drum-dried and reconstituted

creased K values were increased for mango purees and peach fiber solutions, respectively.

Flow index, n, varied between 0.44 to 0.49 and 0.32 to 0.39 using HB and MB models, respectively (Tables 2 and 4). The variation in n exhibited a maximum around the mid-concentration range, extending to minimum at lowest and highest concentrations, 67% and 75%, respectively.

A review of references indicated that less concentrated fruit purees and pulps were easily analyzed over a wider shear rate range and successfully modeled with the HB, MB, or Casson equations (Table 5). The flow data reported in the literature were usually collected over a shear range of up to 3 decades. These used a concentric cylinder or capillary type viscometers. The shear rate range was limited to 49 to 125 s⁻¹ throughout this study because of the high degree of barrel fill of the extruder. At extremely low feed rates a steady flow could not be sustained. As a result, the full viscosity profile could not be observed for the highly concentrated reconstituted peach puree samples evaluated in this study.

As can be seen in Tables 1, 2, 3, and 4 regression coefficients (R²) for all 4 models were over 0.98. Discrepancy in predictions by different models appeared to be minor. Figure 2 indicates that the predictions by all models were nearly superimposed. A 2-parameter Casson model adequately described the flow behavior of peach puree extrudates as well as the Bingham and 3-parameter models (HB and MB). Moreover, results of the nonlinear regression (SAS 1995) indicate that most asymptotic standard errors of parameter estimates were higher than the parameter estimates themselves, thus, revealing overparameterization by the 3-parameter models. Reparameterization of Eq. 6 and 8 (HB and MB equations, respectively) as explained in Ratkowsky (1990) was performed; however, no improvement was noted on the asymptotic standard errors. Reparameterization could be a valuable tool for nonlinear models whose least squares estimators do not approximate the asymptotic properties as well as a model with an estima-

tor that come close to being unbiased, normally distributed, minimum variance estimators (Ratkowsky 1990). Due to the high values of the asymptotic standard errors of the model parameters of HB and MB equations, the confidence intervals were meaninglessly wide. Therefore, the confidence intervals of model parameters for HB and MB equations were not reported in Tables 2 and 4.

NLIN procedure (SAS 1995) was used to determine the parameters of Casson model. R² of Casson equation was as good as HB and MB models, and asymptotic standard errors were much lower than the parameter estimates, indicating no need for reparameterization. The Casson model yielded slightly higher R² than Bingham model. Standardized residual distribution indicated constant error variance and a normal distribution. Outliers were not observed at any concentrations. Therefore, the Casson

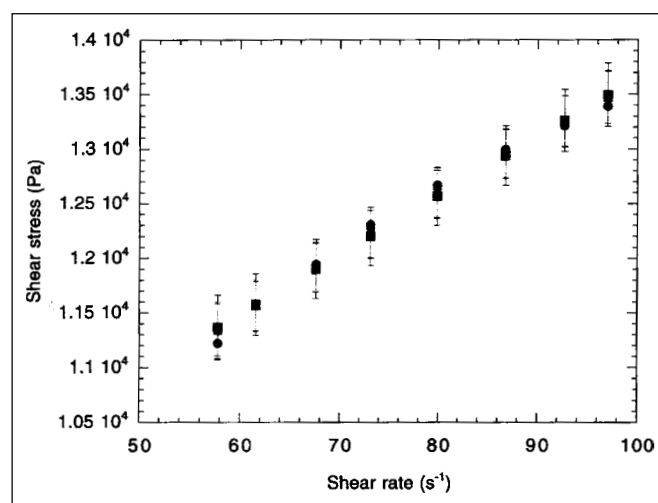


Fig. 2—Applicability of by Bingham, ■; Herschel-Bulkley, ◆; Casson ▲, and Mizrahi-Berk, ▼ models at 75% total solids (●, experimental)

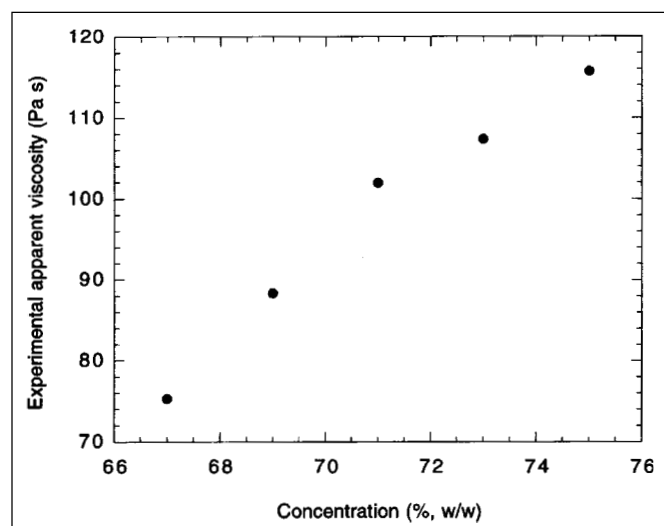


Fig. 3—Change in apparent viscosity of peach extrudates as a function of concentration at 90 s^{-1} shear rate

equation was chosen to be used in the overall viscosity model.

The effect of concentration on the overall apparent viscosity appeared to be linear (Fig. 3). The Casson model was used to represent the effect of shear rate on viscosity. The final nonlinear regression equation is expressed by:

$$\eta = [(\tau_0/\gamma)^{0.5} + \mu_{\infty}^2] \cdot (a + b \cdot m) \quad (9)$$

where m is concentration, and a and b are concentration constants (dimensionless).

PROC NLIN procedure in SAS (1995) was used to determine the model parameters. The computational method chosen was multivariate secant algorithm, which is similar to Gauss-Newton except that the derivatives of the model were estimated from the history of iterations (SAS 1995). The coefficient of multiple determination (R^2) of the overall model was 0.989. The error distribution was normal, and error variance appeared constant. No outliers were detected. It was concluded that there was no sign of overparameterization of the model after examining the asymptotic standard error of the parameter estimates. Table 6 summarizes the model parameters estimated by Eq. 9. Figure 4 illustrates the fit between the predicted apparent viscosity and experimental apparent viscosity. The degree of fit is good as shown by the distribution along the 45° line. Since the proposed equation is a semi-empirical model, its validity is limited to the experimental range studied.

Conclusions

FLOW PROPERTIES OF PEACH EXTRUDATE WERE STUDIED AT different concentrations (total solids): 67%, 69%, 71%, 73%,

Table 6—Parameter estimates for Eq. 9

Parameter	Estimate	Asymptotic Std. Error	Asymp. 95% lower	Confidence Interval upper
τ_0 , Pa	1994.0	43.6	1905.9	2082.0
μ_{∞} , Pa · s	6.71	0.22	6.27	7.14
a	-4.77	0.06	-4.88	-4.66
b	9.30	0.07	9.15	9.45

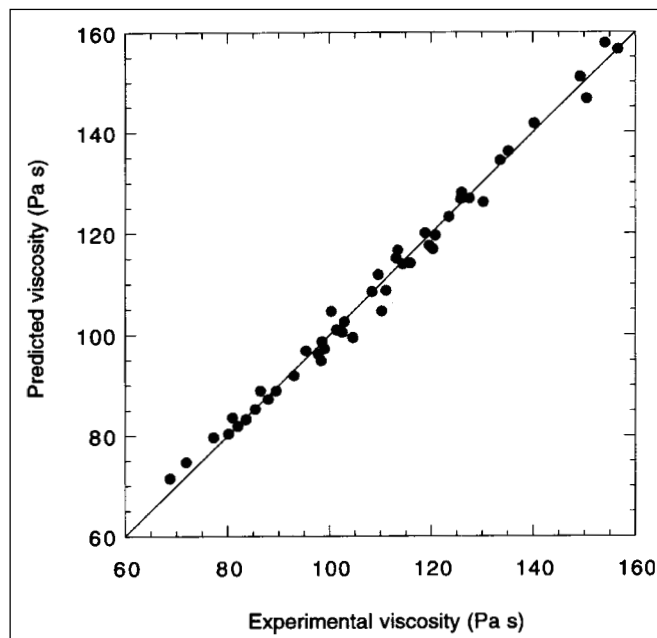


Fig. 4—Predicted apparent viscosity in contrast to experimental apparent viscosity of peach extrudates

and 75% (w/w). Bingham, Herschel-Bulkley, Casson, and Mizrahi-Berk models were fitted to the experimental rheological data. The yield stress of the extrudates increased as concentration increased. The Casson model adequately characterized the flow behavior of peach extrudates formed from partially reconstituted drum-dried purees within the shear rate studied.

The Casson model for the shear rate and a linear expression for the concentration was incorporated in the overall viscosity model. A good predictive model with a high R^2 , valid in the 67% to 75% total solids range, was obtained.

The extruder used in this study is capable of manufacturing products solely from 100% peach. Adaptability of the model to larger scales of production will require scale-up studies. This study contributes to effective design of a larger-scale operation. This study might also be extended for other products based on 100% fruit or fruit-rich formulations.

Materials and Methods

Raw Material. Peach puree at 32 ° Brix was obtained from Sabroso (Medford, Ore., U.S.A.). Water content of the puree was reduced to approximately 4% final moisture by using a double drum dryer (Buflovak, Buffalo, N.Y., U.S.A.) at 134 °C, 0.6 rpm, and a gap of 0.381 mm. Prior to extrusion experiments, drum-dried puree was ground in a food processor (Model DLC-8S, Cuisinart, East Windsor, N.J., U.S.A.). Puree flakes were sieved with a U.S. Standard No. 60 sieve (opening size 250 μm) (Fisher Scientific, Santa Clara, Calif., U.S.A.) to

eliminate the fines. The prepared material was placed in a glass jar and stored in a cold room at 5 °C. Prior to the extrusion, material was allowed to equilibrate at room temperature.

Extrusion. A lab-size, co-rotating twin screw extruder (Haake-Leistritz Micro-18, Sommerville, N.J., U.S.A.) was used to perform the extrusion experiments. A slit die/torque rheometer combination (Haake-Buchler, Paramus, N.J., U.S.A.) was attached to the discharge end of the extruder to measure the rheological properties of the peach melt. The slit dimensions were 2.0 mm high, 20 mm wide, and 160 mm long. The extrud-

er barrel was of modular design with 6 independent heating and cooling zones, each with an length-to-dia ratio of 5:1. Electrical heating and air cooling systems were used to maintain the barrel temperatures constant $\pm 1^\circ\text{C}$. Temperature of each barrel zone and the slit die were set from software and recorded together with the melt temperatures. Melt temperatures were measured by 4 thermocouples (Type J, Omega Engineering, Westport, Conn., U.S.A.) imbedded in the barrel, 1 in the die adapter piece, and 1 in the slit die/torque rheometer. Melt temperatures were also recorded by 2 thermocouples flush with the inside surface, 1 in the slit die and another in the adapter piece. Deionized water was injected through the extruder 2 barrel sections downstream from the feed port. A metering pump (Model N-P31, Bran+Luebbe Inc., Buffalo Grove, Ill., U.S.A.) was used to pump water into the barrel. Three pressure transducers (Type PT422A, Dynisco, Sharon, Mass., U.S.A.) were used to measure the pressure of the melt along the slit die/torque rheometer. The pressure transducers were calibrated at the operating temperature. Two different pressure ranges of the transducers were chosen to increase the accuracy: 0 to 500 psi (3447 kPa) and 0 to 1000 psi (6895 kPa). Another pressure transducer was placed on the adapter piece (range: 0 to 1000 psi (6895 Pa)). Figure 5 illustrates the top view of the slit die.

A gravimetric feeder (Model K2V-T20, K-Tron Corp., Pitman, N.J., U.S.A.) was used to meter the drum-dried puree into the extruder. The 1st (feed port) and 2nd sections of the barrel were unheated to prevent puree particles from sticking to the walls of the feed port.

A computerized data acquisition system (Rheocord 9000, Haake-Buchler, Paramus, N.J., U.S.A.) was used to record set and melt temperatures, rotor speed, torque, and melt pressures along the die and on the adapter piece placed between the barrel and die. Screw speed was 2.5 times the rotor speed. The data acquisition rate was 6 Hz. Data collection was initiated

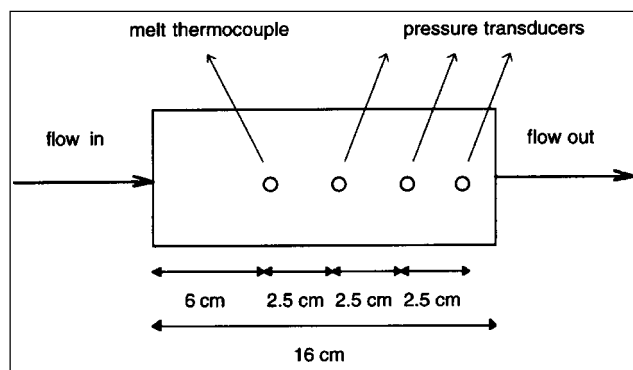


Fig. 5—Simplified top view of the slit die.

ed after reaching the steady state (for example, constant pressure and torque readings).

Die melt temperatures and screw speed were held constant at 40°C and 200 rpm, respectively. A previous study by Akdogan and McHugh (1999) revealed that the effect of screw speed on rheological properties at similar conditions was not significant. Therefore, screw speed was held constant at 200 rpm during this study. Total mass flow rate (drum dried puree and water) was varied from 28 to 64 g/min. Eight to 13 different flow rates were considered for each concentration. Two replicates were performed.

Screw configuration. The details of the screw configuration were given in Akdogan and McHugh (1999).

Moisture content of the feed material. The moisture content of the feed was determined on representative samples using AOAC Method No. 22.013 (AOAC 1970) in a vacuum oven at 70°C for 15 h.

Statistical Analysis. The PROC NLIN procedure in SAS (1995) was used to analyze the experimental data.

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